Search for new physics in the monophoton final state in proton-proton collisions at $\sqrt{s} = 13$ TeV

CMS Collaboration ; Canelli, Maria Florencia ; Kilminster, Benjamin ; Aarrestad, Thea K ; Caminada, Lea ; de Cosa, Annapaoloa ; Del Burgo, Riccardo ; Donato, Silvio ; Galloni, Camilla ; Hinzmann, Andreas ; Hreus, Tomas ; Ngadiuba, Jennifer ; Pinna, Deborah ; Rauco, Giorgia ; Robmann, Peter ; Salerno, Daniel ; Schweiger, Korbinian ; Seitz, Claudia ; Takahashi, Yuta ; Zucchetta, Alberto ; et al

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Search for new physics in the monophoton final state in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

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1 Introduction

One of the most intriguing open questions in physics is the nature of dark matter (DM). While DM is thought to be the dominant nonbaryonic contribution to the matter density of the universe [1], its detection and identification in terrestrial and spaceborne experiments remains elusive. At the CERN LHC, the DM particles may be produced in high-energy proton-proton collisions, if the DM particles interact with the standard model (SM) quarks or gluons via new couplings at the electroweak scale [2, 3]. Although DM particles cannot be directly detected at the LHC, their production could be inferred from an observation of events with a large transverse momentum imbalance (missing transverse momentum, $p_{\mathrm{T}}^{\mathrm{miss}}$, defined in section 2).

Another highly important issue is the hierarchy problem, which involves the large energy gap between the electroweak (M_{EW}) and Planck (M_{Pl}) scales [4]. Proposed solutions to this problem include theories with large extra dimensions, such as the model of Arkani-Hamed, Dimopoulos, Dvali (ADD) [5, 6]. The ADD model postulates that there exist n compactified extra dimensions in which gravitons can propagate freely and that the true scale (M_D) of the gravitational interaction in this $4{+}n$ dimensional space-time is of the same order as M_{EW}. The compactification scale R of the additional dimensions is related to the two gravitational scales by $M_{\mathrm{Pl}}^2 \sim R^n M_D^{n+2}$. For $M_D \sim M_{\mathrm{EW}}$, the cases $n = 1$ and $n = 2$ are ruled out or strongly disfavored by various observations [6], while cases $n \geq 3$ remain

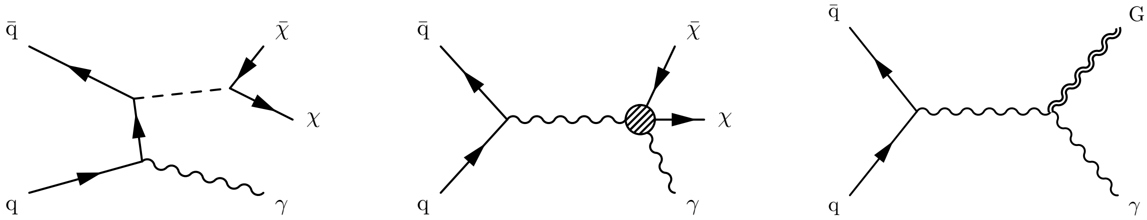

Figure 1. Leading-order diagrams of the simplified DM model (left), electroweak-DM effective interaction (center), and graviton (G) production in the ADD model (right), with a final state of γ and large $p_{\mathrm{T}}^{\mathrm{miss}}$.

to be probed, for example, by collider experiments. The compactification scale R is much greater than $1/M_{\mathrm{EW}}$ for a wide range of n, leading to a near-continuous mass spectrum of Kaluza-Klein graviton states. Although the gravitons would not be observed directly at the LHC, their production would be manifest as events broadly distributed in $p_{\mathrm{T}}^{\mathrm{miss}}$.

In generic models of DM and graviton production, various SM particles can recoil against these undetected particles, producing a variety of final states with significant $p_{\mathrm{T}}^{\mathrm{miss}}$. The monophoton, or $\gamma + p_{\mathrm{T}}^{\mathrm{miss}}$, final state has the advantage of being identifiable with high efficiency and purity. In DM production through a vector or axial vector mediator, a photon can be radiated from incident quarks (figure 1 left). Models of this process have been developed by the CMS-ATLAS Dark Matter Forum [7]. It is also possible that the DM sector couples preferentially to the electroweak sector, leading to an effective interaction $\mathrm{q\bar{q}} \to \mathrm{Z}/\gamma^* \to \gamma\chi\bar{\chi}$ [8], where χ is the DM particle (figure 1 center). In ADD graviton production, the graviton can couple directly to the photon (figure 1 right) or to a quark. In this paper, we examine final states containing large $p_{\mathrm{T}}^{\mathrm{miss}}$ in the presence of a photon with large transverse momentum (p_{T}), and search for an excess of events over the SM prediction. Data collected by the CMS experiment in 2016 with an integrated luminosity of $12.9\,\mathrm{fb}^{-1}$ are analyzed. Results are interpreted in the context of these three models.

The primary irreducible background for the $\gamma + p_{\mathrm{T}}^{\mathrm{miss}}$ signal is SM Z boson production associated with a photon, $\mathrm{Z}(\to \nu\bar{\nu}) + \gamma$. Other SM backgrounds include $\mathrm{W}(\to \ell\nu) + \gamma$ (having a final state photon, and a lepton ℓ that escapes detection), $\mathrm{W} \to \ell\nu$ (where ℓ is misidentified as a photon), γ + jets, quantum chromodynamics (QCD) multijet events (with a jet misidentified as a photon), $\mathrm{t\bar{t}}\gamma$, $\mathrm{VV}\gamma$ (where V refers to a W or a Z boson), $\mathrm{Z}(\to \ell\bar{\ell}) + \gamma$, and noncollision sources, such as beam halo interactions and detector noise.

A previous search in the $\gamma + p_{\mathrm{T}}^{\mathrm{miss}}$ final state using pp collisions at $\sqrt{s} = 8\,\mathrm{TeV}$, corresponding to an integrated luminosity of $19.6\,\mathrm{fb}^{-1}$, was reported by the CMS experiment in ref. [9]. The ATLAS experiment has also reported a similar search in $36.1\,\mathrm{fb}^{-1}$ of pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ [10].

2 The CMS detector and candidate reconstruction

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel ($|\eta| < 1.48$) and two endcap ($1.48 < |\eta| < 3.00$) sections, where η is the pseudorapidity. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

An energy resolution of about 1% is reached within the barrel section of the ECAL for unconverted or late-converting photons with $p_{\mathrm{T}} \geq 60\,\mathrm{GeV}$. The remaining barrel photons have a resolution of about 1.3% up to a pseudorapidity of $|\eta| = 1$, rising to about 2.5% at $|\eta| = 1.4$ [11]. The time resolution of photons at the ECAL is $<200\,\mathrm{ps}$ for depositions $>10\,\mathrm{GeV}$. In the η–ϕ plane, where ϕ is the azimuthal angle, and for $|\eta| < 1.48$, the HCAL cells map onto $5{\times}5$ arrays of ECAL crystals to form calorimeter towers projecting radially outward from the center of the detector. A more detailed description of the CMS detector, together with a definition of the coordinate system and kinematic variables, can be found in ref. [12].

Events of interest are selected using a two-tiered trigger system [13]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a time interval of less than $4\,\mu\mathrm{s}$. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to less than 1 kHz before data storage.

Event reconstruction is performed using a particle-flow (PF) technique [14, 15], which reconstructs and identifies individual particles using an optimized combination of information from all subdetectors. The energy of charged hadrons is determined from a combination of the track momentum and the corresponding ECAL and HCAL energies, corrected for the combined response function of the calorimeters. The energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies. Muon identification and momentum measurements are performed by combining the information from the inner trackers and outer muon chambers.

The PF candidates in each event are clustered into jets via the anti-k_t algorithm [16] with a distance parameter of 0.4. Jet energies, computed from a simple sum of 4-momenta of the constituent PF candidates, are corrected to account for the contributions from particles associated with additional interactions within the same or nearby bunch crossings (pileup), as well as to compensate for the nonlinearities in the measured particle energies. Jet energy corrections are obtained from simulation, and are confirmed through in situ measurements of the energy momentum balance in dijet and photon + jet events.

The uncorrected missing transverse momentum vector ($\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$) is defined as the negative vector sum of the transverse momenta of all PF candidates in an event. This quantity is adjusted with the difference of uncorrected and corrected jets for a consistent and more accurate missing momentum measurement [17]. The magnitude of $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is referred to as the missing transverse momentum, $p_{\mathrm{T}}^{\mathrm{miss}}$.

The reconstruction of photons and electrons begins with the identification of clusters of energy deposited in the ECAL with little or no observed energy in the corresponding HCAL region. For each candidate cluster, the reconstruction algorithm searches for hits in

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the pixel and strip trackers that can be associated with the cluster. Such associated hits are called electron seeds, and are used to initiate a special track reconstruction based on a Gaussian sum filter [18, 19], which is optimized for electron tracks. A "seed veto" removes photon candidates with an associated electron seed.

Selections based on calorimetric information and isolation are applied to distinguish photons from electromagnetic (EM) showers caused by hadrons. The calorimetric requirements for photons comprise $H/E < 0.05$ and $\sigma_{\eta\eta} < 0.0102$, where H/E is the ratio of hadronic to EM energy deposition. The variable $\sigma_{\eta\eta}$, described in detail in ref. [11], represents the width of the electromagnetic shower in the η direction, which is generally larger in showers from hadronic activity. For a photon candidate to be considered as isolated, scalar sums of the transverse momenta of PF charged hadrons, neutral hadrons, and photons within a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$ around the candidate photon must individually fall below the bounds defined for 80% signal efficiency. Only the PF candidates that do not overlap with the EM shower of the candidate photon are included in the isolation sums.

Each PF charged hadron is reconstructed from a track and can be associated with an interaction vertex it originates from. Therefore, the isolation sum over PF charged hadrons should be computed using only the candidates sharing an interaction vertex with the photon candidate. However, because photon candidates are not reconstructed from tracks, their vertex association is ambiguous. When an incorrect vertex is assigned, photon candidates that are not isolated can appear otherwise. To mitigate the rate for accepting nonisolated candidates as photon candidates, the maximum charged hadron isolation value over all vertex hypotheses (worst isolation) is used.

Another consequence of calorimetry-driven reconstruction is that stray ECAL clusters produced by mechanisms other than pp collisions can be misidentified as photons. In particular, beam halo muons that accompany proton beams and penetrate the detector longitudinally, and the interaction of particles in the ECAL photodetectors ("ECAL spikes") have been found to produce spurious photon candidates at nonnegligible rates. To reject these backgrounds, the ECAL signal in the seed crystal of the photon cluster is required to be within ± 3 ns of the arrival time expected for particles originating from a collision. In addition, the candidate cluster must comprise more than a single ECAL crystal. Furthermore, the maximum of the total energy along all possible paths of beam halo particles passing through the cluster is calculated for each photon candidate. This quantity, referred to as the halo total energy, is required to be below a threshold defined to retain 95% of the true photons, while rejecting 80% of the potential halo clusters.

3 Event selection

The integrated luminosity of the analyzed data sample, derived from a preliminary measurement using the method described in [20], is $(12.9 \pm 0.8)\,\mathrm{fb}^{-1}$. The data sample is collected with a single-photon trigger that requires at least one photon candidate with $p_{\mathrm{T}} > 165\,\mathrm{GeV}$. The photon candidate must have $H/E < 0.1$, to reject jets. The photon energy reconstructed in the trigger is less precise relative to that derived later in the offline selection. Therefore, the thresholds in the trigger on both H/E and p_{T}^{γ}, where p_{T}^{γ} is the photon p_{T}, are less restrictive than their offline counterparts. The trigger efficiency is measured to be about 98% for events passing the analysis selection with $p_{\mathrm{T}}^{\gamma} > 175\,\mathrm{GeV}$.

From the recorded data, events are selected by requiring $p_{\mathrm{T}}^{\mathrm{miss}} > 170\,\mathrm{GeV}$ and at least one photon with $p_{\mathrm{T}}^{\gamma} > 175\,\mathrm{GeV}$ in the fiducial region of the ECAL barrel ($|\eta| < 1.44$). Events are rejected if the minimum opening angle between $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ and any of the four highest transverse momenta jets, $\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{jet}})$, is less than 0.5. This requirement significantly suppresses spurious $p_{\mathrm{T}}^{\mathrm{miss}}$ backgrounds from mismeasured jets. Only jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 5$ are considered in the $\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{jet}})$ calculation. The candidate photon transverse momentum vector and $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ must be separated by more than 2 radians. Finally, to reduce the contribution from the $\mathrm{W}(\rightarrow \ell\nu) + \gamma$ process, events are vetoed if they contain an electron or a muon with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ that is separated from the photon by $\Delta R > 0.5$.

4 Signal and background modeling

The SM backgrounds and signal are modeled using both simulated events and recorded data. The two methods are described in the following sections.

4.1 Monte Carlo simulation for signal and background modeling

Monte Carlo (MC) simulation is used to model the signal and some classes of SM background events. For the SM backgrounds, the primary hard interaction is simulated using the MadGraph5_aMC@NLO version 2.2.2 [21] or pythia8.212 [22] generators employing the NNPDF 3.0 [23] leading-order (LO) parton distribution function (PDF) set at the strong coupling value $\alpha_S = 0.130$. Parton showering and hadronization are provided in pythia8.212 through the underlying-event tune CUETP8M1 [24]. Multiple minimum-bias events are overlaid on the primary interaction to model the distribution of pileup in data. Generated particles are processed through the full Geant4-based simulation of the CMS detector [25, 26].

For the DM signal hypothesis, MC simulation samples are produced with MadGraph5_aMC@NLO 2.2.2, requiring $p_{\mathrm{T}}^{\gamma} > 130\,\mathrm{GeV}$ and $|\eta^{\gamma}| < 2.5$. A large number of DM simplified model samples are generated, varying the masses of the mediator and DM particles. Similarly, electroweak-DM effective interaction samples are generated with a range of dark matter masses. For the ADD hypothesis, events are generated using pythia8.212, requiring $p_{\mathrm{T}}^{\gamma} > 130\,\mathrm{GeV}$, with no restriction on the photon pseudorapidity. Samples are prepared in a grid of number of extra dimensions and M_D. The efficiency of the full event selection on these signal models ranges between 0.12 and 0.27 for the DM simplified models, 0.42 and 0.45 for electroweak DM production, and 0.22 and 0.28 for the ADD model, depending on the parameters of the models.

Predictions for signal and background MC yields are rescaled by an overall correction factor (ρ) that accounts for the differences in event selection efficiency between data and simulation. The value of $\rho = 0.94 \pm 0.06$ reflects the product of three correction factors: 0.94 ± 0.01 for photon identification and isolation, 1.00 ± 0.01 for the electron seed veto, and 1.00 ± 0.06 for the combination of the worst isolation, the halo total energy requirement, and the lepton veto. The selection efficiencies are measured in data using the tag-and-probe technique [27]. Events with $\mathrm{Z} \to \mathrm{ee}$ decays are employed for measuring the photon identification and isolation efficiencies, while a $\mathrm{Z} \to \mu\mu\gamma$ sample is utilized to extract the other efficiency factors [28].

The most significant SM backgrounds in this search are from the associated production of a Z or W boson with a high-energy photon, denoted as $\mathrm{Z}(\to \nu\overline{\nu}) + \gamma$ and $\mathrm{W}(\to \ell\nu) + \gamma$. When the Z boson decays into a neutrino-antineutrino pair, the final state exhibits a high-p_{T} photon and large $p_{\mathrm{T}}^{\mathrm{miss}}$. Similarly, if the W boson decays into a lepton-neutrino pair and the lepton escapes detection, the event appears to be $\gamma + p_{\mathrm{T}}^{\mathrm{miss}}$. Together, these processes account for approximately 70% of the SM background, with 50% from $\mathrm{Z}(\to \nu\overline{\nu}) + \gamma$ alone.

The estimation of $\mathrm{Z}(\to \nu\overline{\nu})+\gamma$ and $\mathrm{W}(\to \ell\nu)+\gamma$ backgrounds is based on MadGraph5_aMC@NLO simulations at LO in QCD and with up to two additional partons in the final state. In addition to the selection efficiency correction factor ρ, these samples are weighted event-by-event with the product of two factors. The first factor matches the distribution of the generator-level p_{T}^{γ} to that calculated at next-to-next-to-leading order (NNLO) in QCD using the DYRes program [29]. The second factor, taken from refs. [30, 31], further corrects the backgrounds to account for next-to-leading order (NLO) electroweak effects. The estimated contributions from the $\mathrm{Z}(\to \nu\overline{\nu}) + \gamma$ and $\mathrm{W}(\to \ell\nu) + \gamma$ processes after applying the selections in section 3 are given in table 1, and amount to 215 ± 32 and 57.2 ± 8.0 events, respectively. Statistical and systematic uncertainties are combined in quadrature. The statistical uncertainty is subdominant and is due to the finite size of the simulation sample. Systematic uncertainties in the estimated $\mathrm{Z}(\to \nu\overline{\nu})+\gamma$ and $\mathrm{W}(\to \ell\nu)+\gamma$ yields have four contributions and are summarized in table 2. The first is associated with the PDF and the choice of renormalization and factorization scales (μ_R and μ_F) used in generating the events. The relative uncertainty from these sources are 5.4% and 8.9% in the $\mathrm{Z}(\to \nu\overline{\nu}) + \gamma$ and $\mathrm{W}(\to \ell\nu) + \gamma$ yields, respectively. Uncertainty from the PDF is evaluated by varying the weight of each event based on the standard deviation of the event weight distribution as given by the NNPDF set. Uncertainties from the choice of μ_R and μ_F are evaluated by setting the scales to twice or half the nominal values and taking the minima and maxima of the resulting event weights. Second, the uncertainty due to missing higher-order electroweak corrections is taken as the magnitude of the NLO correction. The uncertainty from this source is 11% for the $\mathrm{Z}(\to \nu\overline{\nu}) + \gamma$ process and 7% for $\mathrm{W}(\to \ell\nu) + \gamma$. The third uncertainty is on the selection efficiency correction factor ρ, with the main contribution from the statistical uncertainties in individual efficiency measurements. A fourth uncertainty is assigned to cover the uncertainties in the jet energy scale [32], photon energy scale [33], pileup, and the scale and resolution in $p_{\mathrm{T}}^{\mathrm{miss}}$. The combined relative uncertainties from the third and fourth categories in the $\mathrm{Z}(\to \nu\overline{\nu}) + \gamma$ and $\mathrm{W}(\to \ell\nu) + \gamma$ yields are 6% and 6.2%, respectively.

To validate the predictions from simulation, observed and MC simulated data are compared in two control regions. One region consists of events with two same-flavor leptons of opposite-charge and a photon, which is dominated by the $\mathrm{Z}(\to \ell\overline{\ell}) + \gamma$ process. The photon is selected by criteria identical to those used in the signal candidate event selection, while the leptons are required to have $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ and the dilepton invariant mass must

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lie between 60 and 120 GeV. Furthermore, the recoil $U^{\ell\bar{\ell}} = |\vec{p}_{\mathrm{T}}^{\mathrm{miss}} + \vec{p}_{\mathrm{T}}^{\ell} + \vec{p}_{\mathrm{T}}^{\bar{\ell}}|$ [27] must be greater than 170 GeV to emulate the $p_{\mathrm{T}}^{\mathrm{miss}}$ in $\mathrm{Z}(\to \nu\bar{\nu}) + \gamma$ events. In addition to simulated $\mathrm{Z}(\to \ell\bar{\ell}) + \gamma$ events, MC samples of $\mathrm{t\bar{t}}\gamma$, $\mathrm{Z}(\to \ell\bar{\ell})$ + jets, and multiboson events are also considered. In total, 68.1 ± 3.8 events are predicted in the dilepton control region, and 64 events are observed. The dominant uncertainty is theoretical. Using the ratio of acceptances between the $\mathrm{Z}(\to \nu\bar{\nu}) + \gamma$ and $\mathrm{Z}(\to \ell\bar{\ell}) + \gamma$ simulations, this validation is used to predict the $\mathrm{Z}(\to \nu\bar{\nu}) + \gamma$ contribution to the candidate sample of 242 ± 35, which is in agreement with the purely simulation-based prediction given previously. The uncertainty in this prediction is mainly due to the limited event yields in the control samples.

The second region is defined by requirements of exactly one electron or muon with $p_{\mathrm{T}} > 30$ GeV, one photon with $p_{\mathrm{T}} > 175$ GeV, $p_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV, and $U^{\ell} = |\vec{p}_{\mathrm{T}}^{\mathrm{miss}} + \vec{p}_{\mathrm{T}}^{\ell}| > 170$ GeV [17]. This region is dominated by $\mathrm{W}(\to \ell\nu) + \gamma$ production. A total of 108 events are observed in this region, where 10.6 ± 1.3 non-$\mathrm{W} + \gamma$ background events are expected. The ratio of the acceptance for $\mathrm{W} + \gamma$ events where the lepton is missed, compared to the acceptance for events where it is identified is estimated from simulation, and is multiplied with the background-subtracted observed yield of this control region. The product, 69.2 ± 7.6, gives a prediction of $\mathrm{W}(\to \ell\nu) + \gamma$ contribution in the signal region that is in agreement with the simulation-based estimate. As with the $\mathrm{Z}(\to \ell\bar{\ell}) + \gamma$ estimate, the dominant uncertainty is theoretical.

The SM $\mathrm{t\bar{t}}\gamma$, $\mathrm{VV}\gamma$, $\mathrm{Z}(\to \ell\bar{\ell}) + \gamma$, $\mathrm{W} \to \ell\nu$, and γ + jets processes are minor ($\sim$10%) backgrounds in the signal region. Although $\mathrm{Z}(\to \ell\bar{\ell}) + \gamma$ and γ+jets do not involve high-p_{T} invisible particles, the former can exhibit large $p_{\mathrm{T}}^{\mathrm{miss}}$ when the leptons are not reconstructed, and the latter when jet energy is severely mismeasured. The estimates for all five processes are taken from MadGraph5_aMC@NLO simulations at leading order in QCD.

4.2 Background estimation using recorded data

An important background consists of $\mathrm{W} \to \mathrm{e}\nu$ events in which the electron is misidentified as a photon. The misidentification occurs because of an inefficiency in seeding electron tracks. A seeding efficiency of $\epsilon = 0.977 \pm 0.002$ for electrons with $p_{\mathrm{T}} > 160$ GeV is measured in data using a tag-and-probe technique in $\mathrm{Z} \to \mathrm{ee}$ events, and is verified with MC simulation. Misidentified electron events are modeled by a proxy sample of electron events, defined in data by requiring an ECAL cluster with a pixel seed. The proxy events must otherwise pass the same criteria used to select signal candidate events. The number of electron proxy events is then scaled by $(1 - \epsilon)/\epsilon$ to yield an estimated contribution of 52.7 ± 4.2 events from electron misidentification. The dominant uncertainty in this estimate is the statistical uncertainty in the measurement of ϵ.

Electromagnetic showers from hadronic activity can also mimic a photon signature. This process is estimated by counting the numbers of events in two different subsets of a low-$p_{\mathrm{T}}^{\mathrm{miss}}$ multijet data sample. The first subset consists of events with a photon candidate that satisfies the signal selection criteria. These events contain both true photons and jets that are misidentified as photons. The second subset comprises events with a candidate photon that meets less stringent shower-shape requirements and inverted isolation criteria with respect to the signal candidates. Nearly all of the candidate photons in these events arise from jet misidentification. The hadron misidentification ratio is defined as the ratio between the number of the misidentified events in the first subset to the total number of events in the second subset. The numerator is estimated by fitting the shower shape distribution of the photon candidate in the first subset with template distributions. For true photons, a template for the shower width is formed using simulated γ+jets events. For jets misidentified as photons, the template is obtained from a sample selected by inverting the charged-hadron isolation and removing the shower-shape requirement entirely. Once the hadron misidentification ratio is computed, it is multiplied by the number of events in the high-$p_{\mathrm{T}}^{\mathrm{miss}}$ control sample with a photon candidate that satisfies the conditions used to select the second subset of the low-$p_{\mathrm{T}}^{\mathrm{miss}}$ control sample. The product, 5.9 ± 1.7 events, is the estimate of the contribution of jet misidentification background in the signal region. The dominant uncertanty is systematic, and accounts for the effects of the fitting procedure, sample purity, photon candidate definition of the control samples, and the sample bias in the jet composition.

Finally, backgrounds from beam halo and spikes in the ECAL are estimated from fits of the angular and timing distributions of the calorimeter clusters. Energy clusters in the ECAL due to beam halo muons are observed to concentrate around $\phi \sim 0$ and π, while all other processes (collision-related processes and ECAL spikes) produce photon candidates that are uniformly distributed in ϕ. The distribution of the cluster seed time provides a cross-check on this background estimate and an independent means to estimate the ECAL spikes contribution. Exploiting these features, a two-component fit of the ϕ distribution with beam halo and uniform templates, and a three-component fit of the cluster seed time using the halo, spike, and prompt-photon templates are performed. In both fits, the halo template is obtained by requiring high halo total energy for candidate-like photon candidates. The timing distribution of the spike background is obtained by inverting the shower shape requirement in the candidate photon selection. The results of the two fits are combined into an uncertainty-weighted average. Beam halo and spike backgrounds of $5.5^{+9.3}_{-5.5}$ and 8.5 ± 6.7 events, respectively, are predicted, where the dominant uncertainty is statistical.

5 Results and interpretation

The estimated number of events and the associated uncertainty for each background process are given in table 1. A total of 400 events are observed in data, which is in agreement with the total expected SM background of 386 ± 36 events.

Distributions of p_{T}^{γ} and $p_{\mathrm{T}}^{\mathrm{miss}}$ for the selected candidate events are shown in figure 2 together with their respective estimated background distributions. A summary of the systematic uncertainties for the background estimates is given in table 2. The quoted systematic uncertainties in table 2 follow the signal and background modeling discussion in section 4.

No excess of data with respect to the SM prediction is observed and limits are set on the aforementioned DM and ADD models. The evaluation of systematic uncertainties for the simulated signal follows the same procedures used for simulated backgrounds (section 4). For each signal model, a 95% confidence level (CL) cross section upper bound is obtained utilizing the asymptotic $\mathrm{CL_s}$ criterion [34–37]. In this method, a Poisson likelihood for

Process	Events
$\mathrm{Z}(\to \nu\overline{\nu}) + \gamma$	215 ± 32
$\mathrm{W}(\to \ell\nu) + \gamma$	57.2 ± 8.0
Electron misidentification	52.7 ± 4.2
ECAL spikes	8.5 ± 6.7
Beam halo	$5.5\,^{+9.3}_{-5.5}$
$\gamma + \text{jets}$	10.1 ± 5.7
$\mathrm{W} \to \mu\nu$	8.5 ± 3.0
$\mathrm{t\bar{t}}\gamma$	8.2 ± 0.6
Jet misidentification	5.9 ± 1.7
$\mathrm{VV}\gamma$	5.5 ± 1.8
$\mathrm{W} \to \tau\nu$	5.2 ± 2.3
$\mathrm{Z}(\to \ell\overline{\ell}) + \gamma$	2.9 ± 0.2
Total background	386 ± 36
Data	400

Table 1. Summary of estimated background and observed candidate events. The quoted uncertainties for the background estimates are obtained by adding the systematic and statistical uncertainties in quadrature.

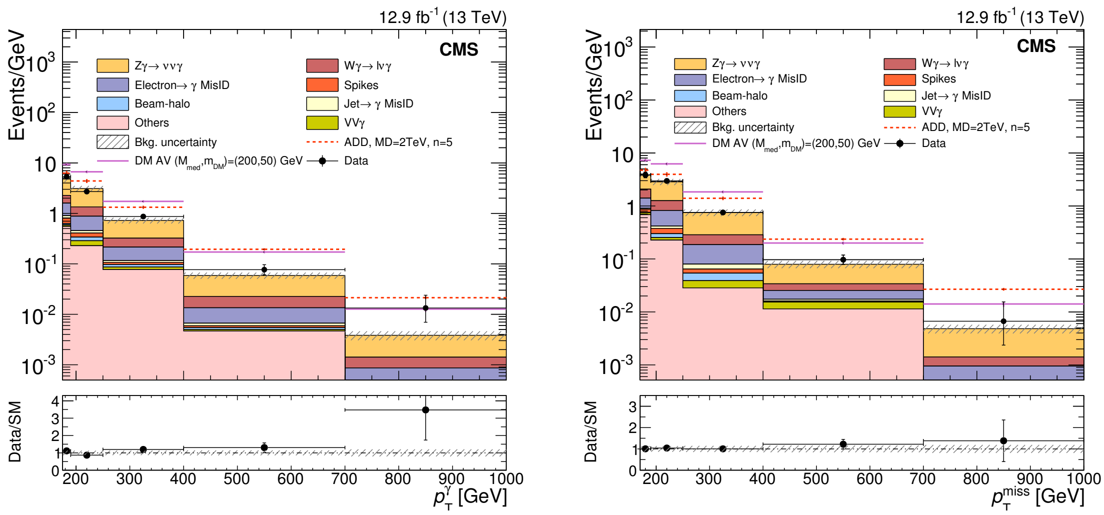

Figure 2. The p_T^γ (left) and p_T^{miss} (right) distributions for the candidate sample, compared with estimated contributions from SM backgrounds. In the legends, "others" includes the contribution from γ+jets, $\mathrm{W} \to \ell\nu$, $\mathrm{Z}(\to \ell\overline{\ell})+\gamma$, and $\mathrm{t\bar{t}}\gamma$ backgrounds. The background uncertainties include statistical and systematic components. The last bin includes the overflow. The lower panel shows the ratio of data and SM background predictions, where the hatched band shows the systematic uncertainty.

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Source	Background component	Value
Integrated luminosity [20]	All simulation-based	6.2
Jet and γ energy scale, $p_{\mathrm{T}}^{\mathrm{miss}}$ resolution	All simulation-based	3–4
Data/simulation factor	All simulation-based	6
PDF, μ_R and μ_F	$\mathrm{Z}(\rightarrow \nu\overline{\nu})+\gamma$, $\mathrm{W}(\rightarrow \ell\nu)+\gamma$	5–9
Electroweak higher-order corrections	$\mathrm{Z}(\rightarrow \nu\overline{\nu})+\gamma$, $\mathrm{W}(\rightarrow \ell\nu)+\gamma$	7–11
Hadronic misidentification ratio	Jet misid.	29
Electron seeding ϵ	Electron misid.	6
ECAL spikes template shape	ECAL spikes	75
Beam halo template shape	Beam halo	+169/−100
$\gamma+$jets yield	$\gamma+$jets	54

Table 2. Summary of relative systematic uncertainties (%) for different background estimates. The middle column indicates the component of the estimated SM background that is affected by each uncertainty.

the observed number of events is maximized under different signal strength hypotheses, taking the systematic uncertainties as nuisance parameters that modify the signal and background predictions. Each nuisance parameter is assigned a log-normal probability distribution, using the systematic uncertainty value as the width. The best fit background predictions differ from the original by at most 4%. Confidence intervals are drawn by comparing these maximum likelihood values to those computed from background-only and signal-plus-background pseudo-data.

5.1 Limits on simplified dark matter models

The simplified DM models proposed by the LHC Dark Matter Forum [7] are designed to facilitate the comparison and translation of various DM search results. In the models considered in this analysis, Dirac DM particles couple to a vector or axial-vector mediator, which in turn couples to the SM quarks. Model points are identified by a set of four parameters: the DM mass m_{DM}, the mediator mass M_{med}, the universal mediator coupling to quarks g_{q}, and the mediator coupling to DM particles g_{DM}. In this analysis, we fix the values of g_{q} and g_{DM} to 0.25 and 1.0, respectively, and scan the M_{med}–m_{DM} plane [38]. The search is not yet sensitive to the spin-0 mediator models defined in ref. [7].

Figure 3 shows the 95% CL cross section upper limits with respect to the corresponding theoretical cross section ($\mu_{95} = \sigma_{95\%}/\sigma_{\mathrm{theory}}$) for the vector and axial-vector mediator scenarios, in the M_{med}–m_{DM} plane. The solid red (lighter) and black (darker) curves are the expected and observed contours of $\mu_{95}=1$ (exclusion contour). The region with $\mu_{95}<1$ is excluded under nominal σ_{theory} hypotheses. The uncertainty in the expected upper limit includes the experimental uncertainties. The uncertainty in the theoretical cross section is translated to the uncertainty in the observed exclusion contour. While there is little difference in kinematic properties between the two scenarios, the production cross section

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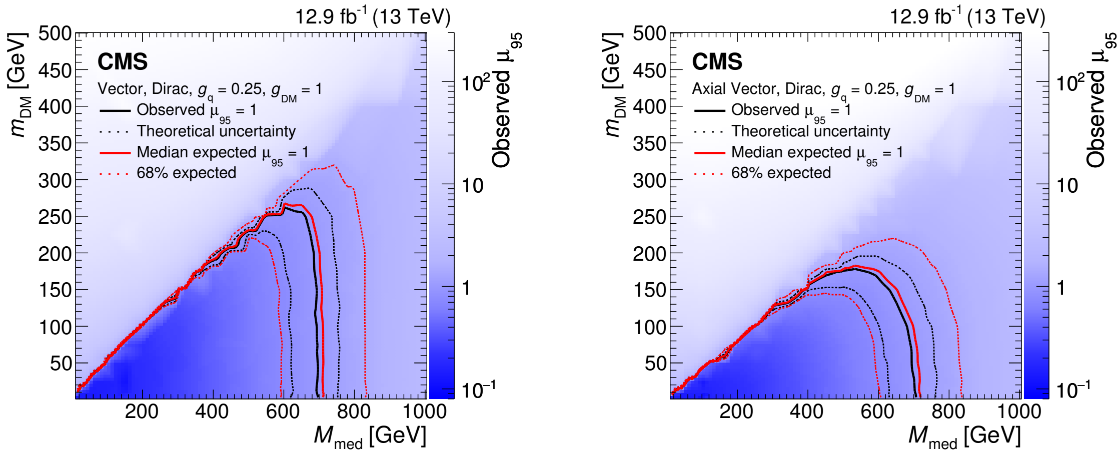

Figure 3. The ratio of 95% CL cross section upper limits to theoretical cross section (μ_{95}), for DM simplified models with vector (left) and axial-vector (right) mediators, assuming $g_q = 0.25$ and $g_{DM} = 1$. Expected and observed $\mu_{95} = 1$ contours are overlaid. The region below the observed contour is excluded.

for heavier dark matter in the vector mediator scenario tends to be higher [7], and therefore the exclusion region broader. For the simplified DM models considered, mediator masses of up to 700 GeV are excluded for small m_{DM} values.

The exclusion contours in figure 3 are also translated into the $\sigma_{SI/SD}$–m_{DM} plane, where $\sigma_{SI/SD}$ are the spin-independent/dependent DM-nucleon scattering cross sections. The translation and presentation of the result follows the prescription given in ref. [38]. In particular, to enable a direct comparison with results from direct detection experiments, these limits are calculated at 90% CL [7]. When compared to the direct detection experiments, the limits obtained from this search provide stronger constraints for dark matter masses less than 2 GeV, assuming spin-independent scattering, or less than 200 GeV, for spin-dependent scattering.

5.2 Limits on electroweak dark matter models

The DM effective field theory (EFT) model contains a dimension-7 contact interaction of type $\gamma\gamma\chi\overline{\chi}$ [8]. The interaction is described by four parameters: the coupling to photons (parametrized in terms of coupling strengths k_1 and k_2), the DM mass m_{DM}, and the suppression scale Λ. Since the interaction cross section is directly proportional to Λ^{-6}, cross section upper limits are translated into lower limits on Λ, assuming $k_1 = k_2 = 1$. The expected and observed lower limits on Λ as a function of m_{DM} are shown in figure 5. Values of Λ up to 600 GeV are excluded at 95% CL.

5.3 Limits on the ADD model

Figure 6 shows the upper limit and the theoretically calculated ADD graviton production cross section for $n = 3$ extra dimensions, as a function of M_D. Lower limits on M_D for various values of n extra dimensions are summarized in table 3, and in figure 7 are compared

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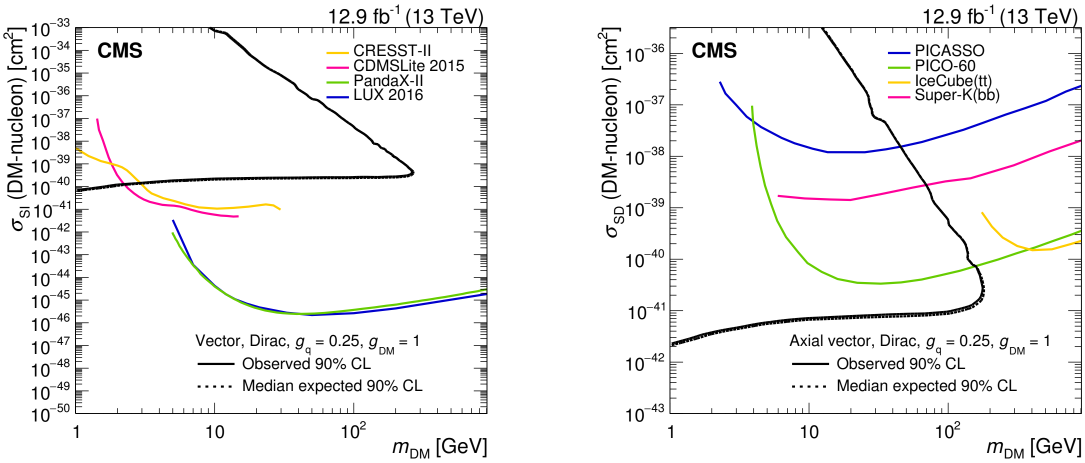

Figure 4. The 90% CL exclusion limits on the χ-nucleon spin-independent (left) and spin-dependent (right) scattering cross sections involving vector and axial-vector operators, respectively, as a function of the m_{DM}. Simplified model DM parameters of $g_{\mathrm{q}} = 0.25$ and $g_{\mathrm{DM}} = 1$ are assumed. The region to the upper left of the contour is excluded. On the plots, the median expected 90% CL curve overlaps the observed 90% CL curve. Also shown are corresponding exclusion contours, where regions above the curves are excluded, from the recent results by CDMSLite [39], LUX [40], PandaX [41], CRESST-II [42], PICO-60 [43], IceCube [44], PICASSO [45] and Super-Kamiokande [46] Collaborations.

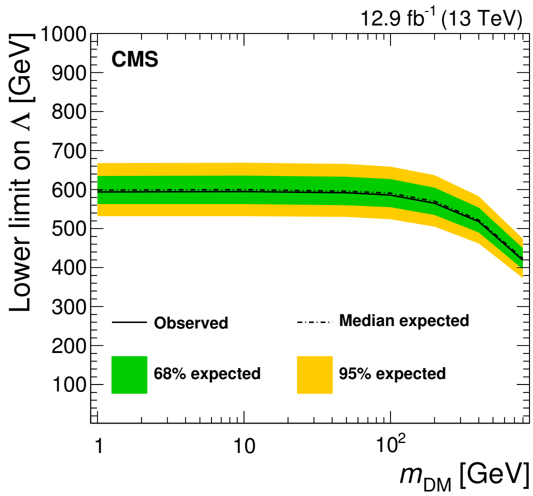

Figure 5. The 95% CL expected and observed lower limits on Λ as a function of m_{DM}, for a dimension-7 operator EFT model assuming $k_1 = k_2 = 1$.

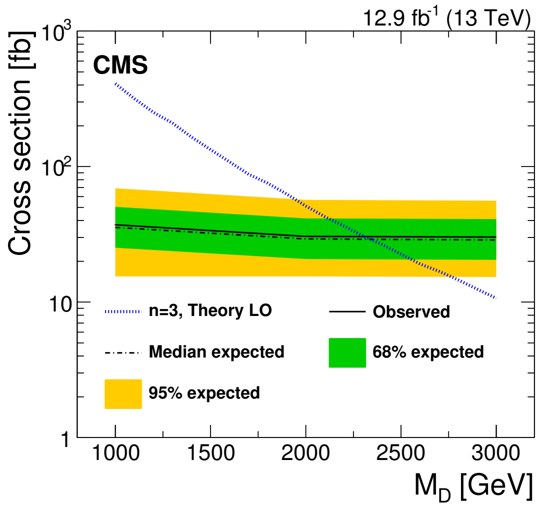

Figure 6. The 95% CL upper limits on the ADD graviton production cross section, as a function of M_D for $n = 3$ extra dimensions.

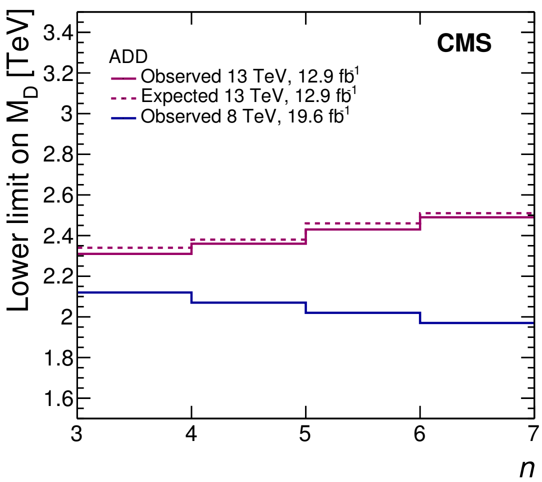

Figure 7. Lower limit on M_D as a function of n, the number of ADD extra dimensions.

to CMS results at $\sqrt{s} = 8\,\text{TeV}$ [9]. Because the graviton production cross section scales as E^n/M_D^{n+2} [47], where E is the typical energy of the hard scattering, M_D can be an increasing or decreasing function of n for a fixed cross section value, approaching E as $n \to \infty$. Note that the value of E is dependent on the center-of-mass energy of the pp collision, and is $\sim$2 TeV for $\sqrt{s} = 8\,\text{TeV}$ and $\sim$3 TeV for $\sqrt{s} = 13\,\text{TeV}$. Values of M_D up to 2.49 TeV for $n = 6$ are excluded by the current analysis.

n	Obs. limit (TeV)	Exp. limit (TeV)
3	2.31	2.34
4	2.36	2.38
5	2.43	2.46
6	2.49	2.51

Table 3. The 95% CL observed and expected lower limits on M_D as a function of n, the number of ADD extra dimensions.

6 Summary

Proton-proton collisions producing large missing transverse momentum and a high transverse momentum photon have been investigated to search for new phenomena, using a data set corresponding to 12.9 fb^{-1} of integrated luminosity recorded at $\sqrt{s} = 13\,\mathrm{TeV}$ at the CERN LHC. No deviations from the standard model predictions are observed. Constraints are set on the production cross sections for dark matter and large extra dimension gravitons at 95% confidence level, which are then translated to limits on the parameters of the individual models. For the simplified dark matter production models considered, the search excludes mediator masses of up to 700 GeV for low-mass dark matter. For an effective dimension-7 photon-dark matter contact interaction, values of Λ up to 600 GeV are excluded. For the ADD model with extra spatial dimensions, values of the fundamental Planck scale up to 2.31–2.49 TeV, depending on the number of extra dimensions, are excluded. These are the most stringent limits in the ADD model to date using the monophoton final state.

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19: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
20: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
21: Also at University of Visva-Bharati, Santiniketan, India
22: Also at Indian Institute of Science Education and Research, Bhopal, India
23: Also at Institute of Physics, Bhubaneswar, India
24: Also at University of Ruhuna, Matara, Sri Lanka
25: Also at Isfahan University of Technology, Isfahan, Iran
26: Also at Yazd University, Yazd, Iran
27: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
28: Also at Università degli Studi di Siena, Siena, Italy
29: Also at Purdue University, West Lafayette, U.S.A.
30: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
31: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
32: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
33: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
34: Also at Institute for Nuclear Research, Moscow, Russia
35: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
36: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
37: Also at University of Florida, Gainesville, U.S.A.
38: Also at P.N. Lebedev Physical Institute, Moscow, Russia
39: Also at California Institute of Technology, Pasadena, U.S.A.
40: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
41: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
42: Also at INFN Sezione di Roma; Sapienza Università di Roma, Rome, Italy
43: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
44: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
45: Also at National and Kapodistrian University of Athens, Athens, Greece
46: Also at Riga Technical University, Riga, Latvia
47: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
48: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
49: Also at Adiyaman University, Adiyaman, Turkey

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50: Also at Istanbul Aydin University, Istanbul, Turkey
51: Also at Mersin University, Mersin, Turkey
52: Also at Cag University, Mersin, Turkey
53: Also at Piri Reis University, Istanbul, Turkey
54: Also at Gaziosmanpasa University, Tokat, Turkey
55: Also at Ozyegin University, Istanbul, Turkey
56: Also at Izmir Institute of Technology, Izmir, Turkey
57: Also at Marmara University, Istanbul, Turkey
58: Also at Kafkas University, Kars, Turkey
59: Also at Istanbul Bilgi University, Istanbul, Turkey
60: Also at Yildiz Technical University, Istanbul, Turkey
61: Also at Hacettepe University, Ankara, Turkey
62: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
63: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
64: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
65: Also at Utah Valley University, Orem, U.S.A.
66: Also at BEYKENT UNIVERSITY, Istanbul, Turkey
67: Also at Erzincan University, Erzincan, Turkey
68: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
69: Also at Texas A&M University at Qatar, Doha, Qatar
70: Also at Kyungpook National University, Daegu, Korea

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